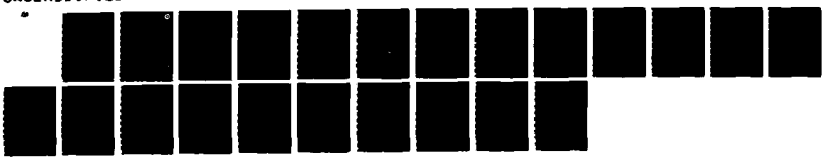
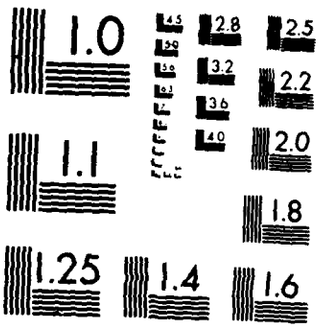
AD-A174 306 ON THE STABILITY OF A STRATIFIED SHEAR LAYER(U) NAVAL RESEARCH LAB WASHINGTON DC P SATYANARAYANA ET AL 19 SEP 86 NRL-MR-5841 1/1

UNCLASSIFIED F/G 20/9 NL





Naval Research Laboratory

Washington, DC 20375-5000 NRL Memorandum Report 5841 September 19, 1986

On the Stability of a Stratified Shear Layer

P. SATYANARAYANA

Science Applications International Corporation
McLean, VA 22102

Y. C. LEE

Science Applications International Corporation
McLean, VA 22102
and
University of Maryland
College Park, MD 20742

J. D. HUBA

Geophysical and Plasma Dynamics Branch
Plasma Physics Division

This work was supported by the Defense Nuclear Agency under Subtask W99QMXWA, work unit 00010 and work unit title "Plasma Structure Evolution."

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

AD-A174306

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5841	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b OFFICE SYMBOL (If applicable) Code 4780	7a. NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b. ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION Defense Nuclear Agency 8b OFFICE SYMBOL (If applicable) RAAE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20305	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 62715H; PROJECT NO. W99QMXWA; TASK NO 00010; WORK UNIT ACCESSION NO. DN580-072

11 TITLE (Include Security Classification)

On the Stability of a Stratified Shear Layer

12 PERSONAL AUTHOR(S)

Satyanarayana,* P., Lee,*+ Y.C. and Huba, J.D. (See page ii)

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Interim	FROM _____ TO _____	1986 September 19	21

16. SUPPLEMENTARY NOTATION

This work was supported by the Defense Nuclear Agency under Subtask W99QMXWA, work unit 00010 and work unit title "Plasma Structure Evolution."

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Linear plasma theory; Fluid stability; Kelvin-Helmholtz instability; Rayleigh-Taylor instability

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The stability of a stratified shear layer is investigated using an exponential density profile and a laminar shear flow with a continuous velocity distribution. It is shown that an exact stability boundary can be obtained from an inhomogeneous inviscid fluid under the action of gravity without the need to impose the Boussinesq approximation. The stability boundary is given by $J = \hat{k}^2 (1 - \beta^2/4 - \hat{k}^2)$ where β is the ratio of the velocity and density gradient scale sizes, J is the Richardson number and $\hat{k}$ is the perpendicular wavenumber normalized to the velocity gradient scale size; this reduces to the stability boundary derived by Drazin in the limit $\beta = 0$. The solution allows for $c = \beta/2$ where c is the normalized phase velocity.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL J. D. Huba	22b TELEPHONE (Include Area Code) (202) 767-3630
	22c OFFICE SYMBOL Code 4780

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

GU.S. Government Printing Office: 1986—607-047

12. PERSONAL AUTHOR(S)

*Science Applications International Corporation, McLean, VA 22102

*+University of Maryland, College Park, MD 20742

CONTENTS

I. INTRODUCTION 1

II. THEORY 2

III. SUMMARY 7

ACKNOWLEDGMENTS 7

REFERENCES 8

ON THE STABILITY OF A STRATIFIED SHEAR LAYER

I. INTRODUCTION

The Kelvin-Helmholtz instability is a widely studied instability driven by velocity shear in neutral fluids as well as in ionized gases[1-6]. In addition to various examples in neutral fluids, the situation of a shear layer under the action of gravity is also encountered in space (e.g., equatorial spread F, the plasmapause) and laboratory (e.g., laser fusion experiments) plasma phenomena. Recent observations show that large velocity shears exist at the equatorward edge of the diffuse auroral boundary[7]. Furthermore, the plasmapause boundary is conjectured to be unstable to a ballooning type shear flow instability[8]. In the case of the equatorial ionosphere, the plasma is confined by a uniform magnetic field and the flow velocity perpendicular to the magnetic field is sheared as a function of the altitude. Gravity is directed opposite to the density gradient so that the system is prone to gravity driven interchange as well as to the shear driven Kelvin-Helmholtz instability. Based on this geometry and physics, linear stability analysis has been performed on a collisional plasma in the equatorial F region of the ionosphere, and a general mode structure equation has been derived[4,5] which reduces to the general Rayleigh equation dealt with in detail by Drazin[2].

In the neutral fluid literature (for example, Drazin[2]) and by Vinas and Madden[8], the Boussinesq approximation is generally assumed in performing the analysis of the general Rayleigh equation; this assumption

Manuscript approved June 12, 1986.

amounts to ignoring all the density gradient terms except the density gradient term that contributes to the bouyancy. In this paper, we relax the Boussinesq approximation and show that the new stability boundary is different than that obtained by Drazin[2]: the stability boundary is dependent on the density gradient, leading to more stringent restrictions on the Richardson number, and the stability boundary is determined for modes with phase velocity half that of the peak background flow velocity. The following analysis is based on a smooth velocity profile and an exponential density gradient.

II. THEORY

The geometry of the plasma and field configuration used in the analysis is as follows: the magnetic field is uniform and in the z direction ($\underline{B} = B\,\hat{z}$), the plasma is inhomogeneous along the x direction, $n = n_0(x)$, gravity is acting along the negative x direction $g = -g\,\hat{x}$, and the flow velocity along the y direction is sheared in the x direction, $\underline{V} = -V_0(x)\,\hat{y}$.

We consider low frequency fluctuations ($\omega << \omega_{ce}$ where ω_{ce} is the electron cyclotron frequency) so that electron inertia is ignored. Two dimensional perturbations are considered. The perturbed quantities vary as $\phi = \phi(x) \exp[-i(k_y y - \omega t)]$, where $\omega = \omega_r + i\gamma$. The equation that describes the perturbed electrostatic potential is given as[4]

$$\frac{\partial^2 \phi}{\partial X^2} + p(X)\frac{\partial \phi}{\partial X} + q(X)\phi = 0, \tag{1}$$

where $p(X)$ and $q(X)$ are given by

$$p(X) = \frac{\partial \ell n n_0}{\partial X}, \tag{2}$$

$$q(X) = -\hat{k}^2 + \frac{1}{\Omega}\left[\frac{\partial^2 U}{\partial x^2} + \frac{\partial \ell n\, n_0}{\partial X}\frac{\partial U}{\partial X} + \frac{(gL_v/\bar{V}_y^2)}{\Omega}\frac{\partial \ell n\, n_0}{\partial X}\right], \tag{3}$$

where $V_0 = \bar{V}_y U(X)$, $c = \omega/k_y\bar{V}_y$, $\Omega = c - U(x)$, $X = x/L_v$, and $\hat{k} = k_y L_v$. Here L_v and L_n are the gradient scale lengths of the velocity and density, respectively. Equation (1) is a general equation that describes Rayleigh-Taylor and Kelvin-Helmholtz instabilities for arbitrary density profiles and drift velocities. This equation is identical to that obtained for counter-streaming neutral fluids in a gravitational field[2].

In this paper we consider an exponential profile for the density such that $n_0(x) = n_0 \exp(\beta X)$ where $\beta = L_v/L_n$ and represent the drift velocity by a smooth profile $U(X) = \tanh(X)$. We let β be arbitrary and thus generalize the problem analyzed by Drazin[2]. This is the main objective of this paper. The coefficients $p(X)$ and $q(X)$ can be rewritten as

$$p(X) = \beta \tag{4}$$

$$q(X) = -\hat{k}^2 + \frac{2\,\mathrm{sech}^2 X\,(-2\tanh X + \beta)}{(c - U)} + \frac{J}{(c - U)^2} \tag{5}$$

where $J = (g/L_n)/(\bar{V}_y^2/L_v^2)$. Using the Boussinesq approximation Drazin[2] set $p = 0$ and ignored β in the second term in q; this leads to the condition $c = 0$. We relax these assumptions in the following analysis.

Using the transformation $\Phi = \phi \exp\left[\int dX\, p(X)/2\right]$ we write (1) as

$$\frac{\partial^2 \Phi}{\partial X^2} + Q(X)\Phi = 0 \tag{6}$$

where $Q(X) = q - p'/2 - p^2/4$. Equations (4) and (5) together with (6) yield

$$\frac{\partial^2 \Phi}{\partial X^2} + \left[-\hat{k}^2 - \frac{\beta^2}{4} + \left(\frac{\mathrm{sech}^2 X\,(-2\tanh X + \beta)}{(c - U)} + \frac{J}{(c - U)^2}\right)\right]\Phi = 0. \tag{7}$$

With U as the independent variable, (7) can be written as

$$(1 - U^2)\frac{\partial^2\Phi}{\partial U^2} - 2U\frac{\partial\Phi}{\partial U} + \left[\frac{-(\hat{k}^2 + \beta^2/4)}{(1 - U^2)} + 2 + \frac{2c - \beta}{(U - c)} + \frac{J}{(U - c)^2(1 - U^2)}\right]\Phi = 0. \tag{8}$$

Equation (8) is a second order differential equation with four singular points at $U = \infty$, c, + 1, and - 1. The new terms in this equation are $-(\beta^2/4)/(1 - U^2)$ and $(2c - \beta)/(U - c)$; the former, obtained by retaining the first derivative term in (1), introduces a lower cut-off in the wavenumber, and the latter, obtained by retaining the cross term involving the density inhomogeneity and velocity inhomogeneity, allows c to take the value $\beta/2$.

We assume a solution to (8) of the form

$$\Phi = (U + 1)^{\mu_+}(U - 1)^{\mu_-}(U - c)^{\lambda}, \tag{9}$$

where the exponents $\mu_\pm$ and λ are determined by

$$2\mu_\pm = \left[\hat{k}^2 + \beta^2/4 - \frac{J}{(1 \pm c)^2}\right]^{1/2} \tag{10}$$

$$(\lambda^2 - \lambda)(1 - c^2) = -\frac{J}{(1 - c^2)}. \tag{11}$$

Note that for $c = 0$ and $\beta = 0$ the exponents (10) and (11) reduce to those given by Drazin[2]. These exponents have to satisfy the condition

$$(\mu_+ + \mu_- + \lambda)(\mu_+ + \mu_- + \lambda + 1) - 2 = 0, \tag{12}$$

as can be seen by matching the coefficients of the constant terms. From (12) we note that $\mu_+ + \mu_- + \lambda = 1$ or -2. The latter condition yields a convergent solution with the constraint $2c - \beta = 0$ or $c = \beta/2$.

Using the definitions for $\mu_\pm$ and λ from (10) and (11) in the condition

$$\mu_+ + \mu_- + \lambda = 1, \tag{13}$$

we obtain

$$J = \hat{k}^2(1 - \beta^2/4 - \hat{k}^2). \tag{14}$$

From (14) the maximum value of J is given as $J_{max} = (1 - \beta^2/4)^2/4$, which occurs at $\hat{k}_{max} = (1/\sqrt{2})(1 - \beta^2/4)^{1/2}$. So the new stability condition is $J > (1 - \beta^2/4)^2/4$.

From (14) we see that for $\beta = 1$ the critical Richardson number is 9/64, which means that for $J > 9/64$ the flow is stable; the cut off wavenumber is $\hat{k} = \sqrt{3}/2$. In comparison, for a Boussinesq fluid the critical J is 1/4 and the cutoff $\hat{k}$ is 1. Finally, the stability boundary is not neutral as was the case with a Boussinesq fluid, but the waves have a phase velocity that is half that of the peak background flow velocity, i.e., $c = 1/2$ as opposed to $c = 0$ for a Boussinesq fluid. Finally, for a fluid in a gravity free field ($J = 0$) the Kelvin-Helmholtz unstable domain is given by $0 < \hat{k} < (1 - \beta^2)^{1/2}$. These conclusions can be clearly seen in Fig. 1, where we plot J versus $\hat{k}$. The figure shows the stability boundary for various values of β. It is worth noting that for $\beta > 2$, that is if the density gradient scale length is half the velocity gradient scale length or less, the Kelvin-Helmholtz instability is stable and the system is unstable to the gravity driven interchange, i.e., only when $J < 0$.

We apply the results to the plasmapause boundary based on the observations of velocity shears observed by Kelley[7] and compare our results with those of Vinas and Madden[8]. The velocity shear V_0/L_v is estimated to be 0.17 Hz; when mapped to the plasmapause region[7] this yields a local Richardson number of - 0.18 [see Ref. 8]. Vinas and Madden[8] show

that $\beta = 1.5$, which when substituted into (15) yields the critical Richardson number $J < 0.047$ for instability. Thus, our calculations suggest that such strong shears may not drive shear flow instability if steep density gradients exist at the same time.

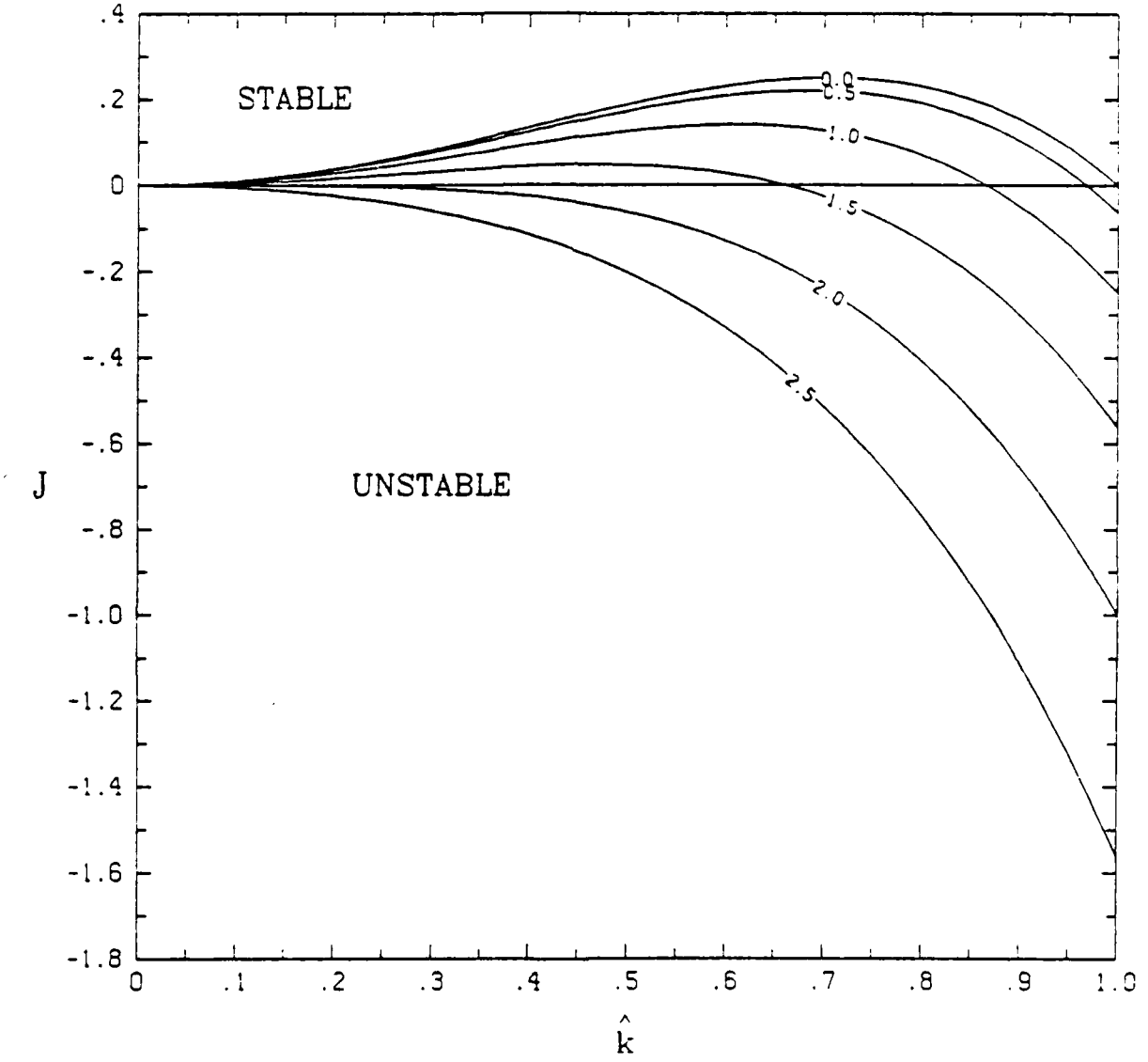


Figure 1. The stability boundary J versus $\hat{k}$ for $\beta = 0.0$, 0.5, 1.0, 1.5, 2.0, and 2.5. The plasma is unstable (stable) in regions below (above) each curve. The case $\beta = 0$ corresponds to the Boussinesq fluid treated by Drazin. Note that for $\beta \geq 2$, $J < 0$ is required for instability.

III. SUMMARY

In summary, we have shown that the mode equation for a stratified shear layer under the action of gravity can be solved for stability boundary without the need to impose the Boussinesq approximation. For $L_n = L_v$ $\beta = 1$, the critical Richardson number is 9/64 as opposed to 1/4 and the unstable wavenumber domain is smaller with a cut off for $J = 0$ at $\hat{k} = \sqrt{3}/2$ rather than at $\hat{k} = 1$. In addition, the waves do not have a zero phase velocity but a phase velocity that is half the peak background flow velocity. These changes are due to the density gradient terms that were ignored using the Boussinesq approximation. In addition, we have shown that plasmapause boundary may not be unstable to shear flow ballooning instability if strong density gradients exist in conjunction with strong shears at the diffuse auroral boundary at ionospheric heights.

ACKNOWLEDGMENTS

This work was supported by the Defense Nuclear Agency.

REFERENCES

1. S. Chandrasekhar, Hydrodynamic and Hydromagnetic Stability, Int. Ser. Monographs on Physics, Clarendon Press, Oxford, p. 494 (1961).
2. P.G. Drazin, J. Fluid Mech., 4, 214 (1958).
3. P.G. Drazin and W.H. Reid, Hydrodynamic Stability, Cambridge University Press, Cambridge, p. 124 (1980).
4. P.N. Guzdar, P. Satyanarayana, J.D. Huba, and S.L. Ossakow, Geophys. Res. Lett., 9, 547 (1982).
5. P. Satyanarayana, P.N. Guzdar, J.D. Huba, and S.L. Ossakow, J. Geophys. Res., 89, 2945 (1984).
6. A.B. Mikhailovskii, Theory of Plasma Instabilities, Vol. II, Consultants Bureau, New York, p. 141 (1974).
7. M.C. Kelley, J. Geophys. Res., 91, 3225 (1986).
8. A. Vinas and T.R. Madden, J. Geophys. Res., 91, 1519 (1986).

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

ASSISTANT SECRETARY OF DEFENSE
COMM, CMD, CONT 7 INTELL
WASHINGTON, DC 20301

DIRECTOR
COMMAND CONTROL TECHNICAL CENTER
PENTAGON RM BE 685
WASHINGTON, DC 20301
01CY ATTN C-650
01CY ATTN C-312 R. MASON

DIRECTOR
DEFENSE ADVANCED RSCH PROJ AGENCY
ARCHITECT BUILDING
1400 WILSON BLVD.
ARLINGTON, VA 22209
01CY ATTN NUCLEAR MONITORING RESEARCH
01CY ATTN STRATEGIC TECH OFFICE

DEFENSE COMMUNICATION ENGINEER CENTER
1860 WIEHLE AVENUE
RESTON, VA 22090
01CY ATTN CODE R410
01CY ATTN CODE R812

DIRECTOR
DEFENSE NUCLEAR AGENCY
WASHINGTON, DC 20305
01CY ATTN STVL
04CY ATTN TITL
01CY ATTN DDST
03CY ATTN RAAE

COMMANDER
FIELD COMMAND
DEFENSE NUCLEAR AGENCY
KIRTLAND, AFB, NM 87115
01CY ATTN FCPR

DEFENSE NUCLEAR AGENCY
SAO/DNA
BUILDING 20676
KIRTLAND AFB, NM 87115
01CY D.C. THORNBURG

DIRECTOR
INTERSERVICE NUCLEAR WEAPONS SCHOOL
KIRTLAND AFB, NM 87115
01CY ATTN DOCUMENT CONTROL

JOINT PROGRAM MANAGEMENT OFFICE
WASHINGTON, DC 20330
01CY ATTN J-3 WWMCCS EVALUATION OFFICE

DIRECTOR
JOINT STRAT TGT PLANNING STAFF
OFFUTT AFB
OMAHA, NB 68113
01CY ATTN JSTPS/JLKS
01CY ATTN JPST G. GOETZ

CHIEF
LIVERMORE DIVISION FLD COMMAND DNA
DEPARTMENT OF DEFENSE
LAWRENCE LIVERMORE LABORATORY
P.O. BOX 808
LIVERMORE, CA 94550
01CY ATTN FCPRL

COMMANDANT
NATO SCHOOL (SHAPE)
APO NEW YORK 09172
01CY ATTN U.S. DOCUMENTS OFFICER

UNDER SECY OF DEF FOR RSCH & ENGRG
DEPARTMENT OF DEFENSE
WASHINGTON, DC 20301
01CY ATTN STRATEGIC & SPACE SYSTEMS (OS)

COMMANDER/DIRECTOR
ATMOSPHERIC SCIENCES LABORATORY
U.S. ARMY ELECTRONICS COMMAND
WHITE SANDS MISSILE RANGE, NM 88002
01CY ATTN DELAS-EO, F. NILES

DIRECTOR
BMD ADVANCED TECH CTR
HUNTSVILLE OFFICE
P.O. BOX 1500
HUNTSVILLE, AL 35807
01CY ATTN ATC-T MELVIN T. CAPPS
01CY ATTN ATC-O W. DAVIES
01CY ATTN ATC-R DON RUSS

PROGRAM MANAGER
BMD PROGRAM OFFICE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333
01CY ATTN DACS-BMT J. SHEA

CHIEF C-E- SERVICES DIVISION
U.S. ARMY COMMUNICATIONS CMD
PENTAGON RM 1B269
WASHINGTON, DC 20310
01CY ATTN C- E-SERVICES DIVISION

COMMANDER
FRADCOM TECHNICAL SUPPORT ACTIVITY
DEPARTMENT OF THE ARMY
FORT MONMOUTH, N.J. 07703
01CY ATTN DRSEL-NL-RD H. BENNET
01CY ATTN DRSEL-PL-ENV H. BOMKE
01CY ATTN J.E. QUIGLEY

COMMANDER
U.S. ARMY COMM-ELEC ENGRG INSTAL AGY
FT. HUACHUCA, AZ 85613
01CY ATTN CCC-EMEO GEORGE LANE

COMMANDER
U.S. ARMY FOREIGN SCIENCE & TECH CTR
220 7TH STREET, NE
CHARLOTTESVILLE, VA 22901
01CY ATTN DRXST-SD

COMMANDER
U.S. ARMY MATERIAL DEV & READINESS CMD
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333
01CY ATTN DRCLDC J.A. BENDER

COMMANDER
U.S. ARMY NUCLEAR AND CHEMICAL AGENCY
7500 BACKLICK ROAD
BLDG 2073
SPRINGFIELD, VA 22150
01CY ATTN LIBRARY

DIRECTOR
U.S. ARMY BALLISTIC RESEARCH
LABORATORY
ABERDEEN PROVING GROUND, MD 21005
01CY ATTN TECH LIBRARY,
EDWARD BAICY

COMMANDER
U.S. ARMY SATCOM AGENCY
FT. MONMOUTH, NJ 07703
01CY ATTN DOCUMENT CONTROL

COMMANDER
U.S. ARMY MISSILE INTELLIGENCE AGENCY
REDSTONE ARSENAL, AL 35809
01CY ATTN JIM GAMBLE

DIRECTOR
U.S. ARMY TRADOC SYSTEMS ANALYSIS
ACTIVITY
WHITE SANDS MISSILE RANGE, NM 88002
01CY ATTN ATAA-SA
01CY ATTN TCC/F. PAYAN JR.
01CY ATTN ATTA-TAC LTC J. HESSE

COMMANDER
NAVAL ELECTRONIC SYSTEMS COMMAND
WASHINGTON, DC 20360
01CY ATTN NAVALEX 034 T. HUGHES
01CY ATTN PME 117
01CY ATTN PME 117-T
01CY ATTN CODE 5011

COMMANDING OFFICER
NAVAL INTELLIGENCE SUPPORT CTR
4301 SUITLAND ROAD, BLDG. 5
WASHINGTON, DC 20390
01CY ATTN MR. DUBBIN STIC 12
01CY ATTN NISC-50
01CY ATTN CODE 5404 J. GALET

COMMANDER
NAVAL OCCEAN SYSTEMS CENTER
SAN DIEGO, CA 92152
01CY ATTN J. FERGUSON

NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20375
01CY ATTN CODE 4700 S.L. Ossakow,
26 CYS IF UNCLASS
(01CY IF CLASS)
ATTN CODE 4780 J.D. HUBA, 50
CYS IF UNCLASS, 01CY IF CLASS
01CY ATTN CODE 4701 I. VITKOVITSKY
01CY ATTN CODE 7500
01CY ATTN CODE 7550
01CY ATTN CODE 7580
01CY ATTN CODE 7551
01CY ATTN CODE 7555
01CY ATTN CODE 4730 E. MCLEAN
01CY ATTN CODE 4752
01CY ATTN CODE 4730 B. RIPIN
20CY ATTN CODE 2628

COMMANDER
NAVAL SPACE SURVEILLANCE SYSTEM
DAHLGREN, VA 22448
01CY ATTN CAPT J.H. BURTON

OFFICER-IN-CHARGE
NAVAL SURFACE WEAPONS CENTER
WHITE OAK, SILVER SPRING, MD 20910
01CY ATTN CODE F31

DIRECTOR
STRATEGIC SYSTEMS PROJECT OFFICE
DEPARTMENT OF THE NAVY
WASHINGTON, DC 20376
01CY ATTN NSP-2141
01CY ATTN NSSP-2722 FRED WIMBERLY

COMMANDER
NAVAL SURFACE WEAPONS CENTER
DAHLGREN LABORATORY
DAHLGREN, VA 22448
01CY ATTN CODE DF-14 R. BUTLER

OFFICER OF NAVAL RESEARCH
ARLINGTON, VA 22217
01CY ATTN CODE 465
01CY ATTN CODE 461
01CY ATTN CODE 402
01CY ATTN CODE 420
01CY ATTN CODE 421

COMMANDER
AEROSPACE DEFENSE COMMAND/DC
DEPARTMENT OF THE AIR FORCE
ENT AFB, CO 80912
01CY ATTN DC MR. LONG

COMMANDER
AEROSPACE DEFENSE COMMAND/XPD
DEPARTMENT OF THE AIR FORCE
ENT AFB, CO 80912
01CY ATTN XPDQQ
01CY ATTN XP

AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731
01CY ATTN OPR HAROLD GARDNER
01CY ATTN LKB
KENNETH S.W. CHAMPION
01CY ATTN OPR ALVA T. STAIR
01CY ATTN PHD JURGEN BUCHAU
01CY ATTN PHD JOHN P. MULLEN

AF WEAPONS LABORATORY
KIRTLAND AFT, NM 87117
01CY ATTN SUL
01CY ATTN CA ARTHUR H. GUENTHER
01CY ATTN NTYCE 1LT. G. KRAJEI

AFTAC
PATRICK AFB, FL 32925
01CY ATTN TN

AIR FORCE AVIONICS LABORATORY
WRIGHT-PATTERSON AFB, OH 45433
01CY ATTN AAD WADE HUNT
01CY ATTN AAD ALLEN JOHNSON

DEPUTY CHIEF OF STAFF
RESEARCH, DEVELOPMENT, & ACQ
DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC 20330
01CY ATTN AFRDQ

HEADQUARTERS
ELECTRONIC SYSTEMS DIVISION
DEPARTMENT OF THE AIR FORCE
HANSCOM AFB, MA 01731-5000
01CY ATTN J. DEAS
ESD/SCD-4

COMMANDER
FOREIGN TECHNOLOGY DIVISION, AFSC
WRIGHT-PATTERSON AFB, OH 45433
01CY ATTN NICD LIBRARY
01CY ATTN ETDP B. BALLARD

COMMANDER
ROME AIR DEVELOPMENT CENTER, AFSC
GRIFFISS AFB, NY 13441
01CY ATTN DOC LIBRARY/TSLD
01CY ATTN OCSE V. COYNE

STRATEGIC AIR COMMAND/XPFS
OFFUTT AFB, NB 68113
01CY ATTN XPFS

SAMSO/SK
P.O. BOX 92960
WORLDWAY POSTAL CENTER
LOS ANGELES, CA 90009
01CY ATTN SKA (SPACE COMM SYSTEMS)
M. CLAVIN

SAMSO/MN
NORTON AFB, CA 92409
(MINUTEMAN)
01CY ATTN MNNL

COMMANDER
ROME AIR DEVELOPMENT CENTER, AFSC
HANSCOM AFB, MA 01731
01CY ATTN EEP A. LORENTZEN

DEPARTMENT OF ENERGY
LIBRARY ROOM G-042
WASHINGTON, DC 20545
01CY ATTN DOC CON FOR A. LABOWITZ

DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE
P.O. BOX 5400
ALBUQUERQUE, NM 87115
01CY ATTN DOC CON FOR D. SHERWOOD

EG&G, INC.
LOS ALAMOS DIVISION
P.O. BOX 809
LOS ALAMOS, NM 85544
01CY ATTN DOC CON FOR J. BREEDLOVE

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY
P.O. BOX 808
LIVERMORE, CA 94550
01CY ATTN DOC CON FOR TECH INFO DEPT
01CY ATTN DOC CON FOR L-389 R. OTT
01CY ATTN DOC CON FOR L-31 R. HAGER

LOS ALAMOS NATIONAL LABORATORY
P.O. BOX 1663
LOS ALAMOS, NM 87545
01CY ATTN DOC CON FOR J. WOLCOTT
01CY ATTN DOC CON FOR R.F. TASCHEK
01CY ATTN DOC CON FOR E. JONES
01CY ATTN DOC CON FOR J. MALIK
01CY ATTN DOC CON FOR R. JEFFRIES
01CY ATTN DOC CON FOR J. ZINN
01CY ATTN DOC CON FOR D. WESTERVELT
01CY ATTN D. SAPPENFIELD

LOS ALAMOS NATIONAL LABORATORY
MS D438
LOS ALAMOS, NM 87545
01CY ATTN S.P. GARY
01CY ATTN J. BOROVSKY

SANDIA LABORATORIES
P.O. BOX 5800
ALBUQUERQUE, NM 87115
01CY ATTN DOC CON FOR W. BROWN
01CY ATTN DOC CON FOR A. THORNBROUGH
01CY ATTN DOC CON FOR T. WRIGHT
01CY ATTN DOC CON FOR D. DAHLGREN
01CY ATTN DOC CON FOR 3141
01CY ATTN DOC CON FOR SPACE PROJECT DIV

SANDIA LABORATORIES
LIVERMORE LABORATORY
P.O. BOX 969
LIVERMORE, CA 94550
01CY ATTN DOC CON FOR B. MURPHEY
01CY ATTN DOC CON FOR T. COOK

OFFICE OF MILITARY APPLICATION
DEPARTMENT OF ENERGY
WASHINGTON, DC 20545
01CY ATTN DOC CON DR. YO SONG

NATIONAL OCEANIC & ATMOSPHERIC ADMIN
ENVIRONMENTAL RESEARCH LABORATORIES
DEPARTMENT OF COMMERCE
BOULDER, CO 80302
01CY ATTN R. GRUBB

DEPARTMENT OF DEFENSE CONTRACTORS

AEROSPACE CORPORATION
P.O. BOX 92957
LOS ANGELES, CA 90009
01CY ATTN I. GARFUNKEL
01CY ATTN T. SALMI
01CY ATTN V. JOSEPHSON
01CY ATTN S. BOWER
01CY ATTN D. OLSEN

ANALYTICAL SYSTEMS ENGINEERING CORP
5 OLD CONCORD ROAD
BURLINGTON, MA 01803
01CY ATTN RADIO SCIENCES

AUSTIN RESEARCH ASSOC., INC.
1901 RUTLAND DRIVE
AUSTIN, TX 78758
01CY ATTN L. SLOAN
01CY ATTN R. THOMPSON

BERKELEY RESEARCH ASSOCIATES, INC.
P.O. BOX 983
BERKELEY, CA 94701
01CY ATTN J. WORKMAN
01CY ATTN C. PRETTIE
01CY ATTN S. BRECHT

BOEING COMPANY, THE
P.O. BOX 3707
SEATTLE, WA 98124
01CY ATTN G. KEISTER
01CY ATTN D. MURRAY
01CY ATTN G. HALL
01CY ATTN J. KENNEY

CHARLES STARK DRAPER LABORATORY, INC.
555 TECHNOLOGY SQUARE
CAMBRIDGE, MA 02139
01CY ATTN D.B. COX
01CY ATTN J.P. GILMORE

COMSAT LABORATORIES
22300 COMSAT DRIVE
CLARKSBURG, MD 20871
01CY ATTN G. HYDE

CORNELL UNIVERSITY
DEPARTMENT OF ELECTRICAL ENGINEERING
ITHACA, NY 14850
01CY ATTN D.T. FARLEY, JR.

ELECTROSPACE SYSTEMS, INC.
BOX 1359
RICHARDSON, TX 75080
01CY ATTN H. LOGSTON
01CY ATTN SECURITY (PAUL PHILLIPS)

EOS TECHNOLOGIES, INC.
606 Wilshire Blvd.
Santa Monica, CA 90401
01CY ATTN C.B. GABBARD
01CY ATTN R. LELEVIER

ESL, INC.
495 JAVA DRIVE
SUNNYVALE, CA 94086
01CY ATTN J. ROBERTS
01CY ATTN JAMES MARSHALL

GENERAL ELECTRIC COMPANY
SPACE DIVISION
VALLEY FORGE SPACE CENTER
GODDARD BLVD KING OF PRUSSIA
P.O. BOX 8555
PHILADELPHIA, PA 19101
01CY ATTN M.H. BORTNER
SPACE SCI LAB

GENERAL ELECTRIC TECH SERVICES
CO., INC.
HMES
COURT STREET
SYRACUSE, NY 13201
01CY ATTN G. MILLMAN

GEOPHYSICAL INSTITUTE
UNIVERSITY OF ALASKA
FAIRBANKS, AK 99701
(ALL CLASS ATTN: SECURITY OFFICER)
01CY ATTN T.N. DAVIS (UNCLASS ONLY)
01CY ATTN NEAL BROWN (UNCLASS ONLY)

GTE SYLVANIA, INC.
ELECTRONICS SYSTEMS GRP-EASTERN DIV
77 A STREET
NEEDHAM, MA 02194
  01CY ATTN DICK STEINHOF

HSS, INC.
2 ALFRED CIRCLE
BEDFORD, MA 01730
  01CY ATTN DONALD HANSEN

ILLINOIS, UNIVERSITY OF
107 COBLE HALL
150 DAVENPORT HOUSE
CHAMPAIGN, IL 61820
  (ALL CORRES ATTN DAN MCCLELLAND)
  01CY ATTN K. YEH

INSTITUTE FOR DEFENSE ANALYSES
1801 NO. BEAUREGARD STREET
ALEXANDRIA, VA 22311
  01CY ATTN J.M. AEIN
  01CY ATTN ERNEST BAUER
  01CY ATTN HANS WOLFARD
  01CY ATTN JOEL BENGSTON

INTL TEL & TELEGRAPH CORPORATION
500 WASHINGTON AVENUE
NUTLEY, NJ 07110
  01CY ATTN TECHNICAL LIBRARY

JAYCOR
11011 TORREYANA ROAD
P.O. BOX 85154
SAN DIEGO, CA 92138
  01CY ATTN J.L. SPERLING

JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
JOHNS HOPKINS ROAD
LAUREL, MD 20810
  01CY ATTN DOCUMENT LIBRARIAN
  01CY ATTN THOMAS POTEMRA
  01CY ATTN JOHN DASSOULAS

KAMAN SCIENCES CORP
P.O. BOX 7463
COLORADO SPRINGS, CO 80933
  01CY ATTN T. MEAGHER

KAMAN TEMPO-CENTER FOR ADVANCED STUDIES
816 STATE STREET (P.O DRAWER QQ)
SANTA BARBARA, CA 93102
  01CY ATTN DASIAC
  01CY ATTN WARREN S. KNAPP
  01CY ATTN WILLIAM MCNAMARA
  01CY ATTN B. GAMBILL

LINKABIT CORP
10453 ROSELLE
SAN DIEGO, CA 92121
  01CY ATTN IRWIN JACOBS

LOCKHEED MISSILES & SPACE CO., INC
P.O. BOX 504
SUNNYVALE, CA 94088
  01CY ATTN DEPT 60-12
  01CY ATTN D.R. CHURCHILL

LOCKHEED MISSILES & SPACE CO., INC.
3251 HANOVER STREET
PALO ALTO, CA 94304
  01CY ATTN MARTIN WALT DEPT 52-12
  01CY ATTN W.L. IMHOF DEPT 52-12
  01CY ATTN RICHARD G. JOHNSON
    DEPT 52-12
  01CY ATTN J.B. CLADIS DEPT 52-12

MARTIN MARIETTA CORP
ORLANDO DIVISION
P.O. BOX 5837
ORLANDO, FL 32805
  01CY ATTN R. HEFFNER

MCDONNEL DOUGLAS CORPORATION
5301 BOLSA AVENUE
HUNTINGTON BEACH, CA 92647
  01CY ATTN N. HARRIS
  01CY ATTN J. MOULE
  01CY ATTN GEORGE MROZ
  01CY ATTN W. OLSON
  01CY ATTN R.W. HALPRIN
  01CY ATTN TECHNICAL
    LIBRARY SERVICES

MISSION RESEARCH CORPORATION
735 STATE STREET
SANTA BARBARA, CA 93101
01CY ATTN P. FISCHER
01CY ATTN W.F. CREVIER
01CY ATTN STEVEN L. GUTSCHE
01CY ATTN R. BOGUSCH
01CY ATTN R. HENDRICK
01CY ATTN RALPH KILB
01CY ATTN DAVE SOWLE
01CY ATTN F. FAJEN
01CY ATTN M. SCHEIBE
01CY ATTN CONRAD L. LONGMIRE
01CY ATTN B. WHITE
01CY ATTN R. STAGAT

MISSION RESEARCH CORP.
1720 RANDOLPH ROAD, S.E.
ALBUQUERQUE, NM 87106
01CY R. STELLINGWERF
01CY M. ALME
01CY L. WRIGHT

MITRE CORP
WESTGATE RESEARCH PARK
1820 DOLLY MADISON BLVD
MCLEAN, VA 22101
01CY ATTN W. HALL
01CY ATTN W. FOSTER

PACIFIC-SIERRA RESEARCH CORP
12340 SANTA MONICA BLVD.
LOS ANGELES, CA 90025
01CY ATTN E.C. FIELD, JR.

PENNSYLVANIA STATE UNIVERSITY
IONOSPHERE RESEARCH LAB
318 ELECTRICAL ENGINEERING EAST
UNIVERSITY PARK, PA 16802
(NO CLASS TO THIS ADDRESS)
01CY ATTN IONOSPHERIC RESEARCH LAB

PHOTOMETRICS, INC.
4 ARROW DRIVE
WOBURN, MA 01801
01CY ATTN IRVING L. KOFSKY

PHYSICAL DYNAMICS, INC.
P.O. BOX 3027
BELLEVUE, WA 98009
01CY ATTN E.J. FREMOUW

PHYSICAL DYNAMICS, INC.
P.O. BOX 10367
OAKLAND, CA 94610
ATTN A. THOMSON

R & D ASSOCIATES
P.O. BOX 9695
MARINA DEL REY, CA 90291
01CY ATTN FORREST GILMORE
01CY ATTN WILLIAM B. WRIGHT, JR.
01CY ATTN WILLIAM J. KARZAS
01CY ATTN H. ORY
01CY ATTN C. MACDONALD

RAYTHEON CO.
528 BOSTON POST ROAD
SUDBURY, MA 01776
01CY ATTN BARBARA ADAMS

RIVERSIDE RESEARCH INSTITUTE
330 WEST 42nd STREET
NEW YORK, NY 10036
01CY ATTN VINCE TRAPANI

SCIENCE APPLICATIONS
INTERNATIONAL INCORPORATED
1150 PROSPECT PLAZA
LA JOLLA, CA 92037
01CY ATTN LEWIS M. LINSON
01CY ATTN DANIEL A. HAMLIN
01CY ATTN E. FRIEMAN
01CY ATTN E.A. STRAKER
01CY ATTN CURTIS A. SMITH

SCIENCE APPLICATIONS
INTERNATIONAL CORPORATION
1710 GOODRIDGE DR.
MCLEAN, VA 22102
01CY J. COCKAYNE
01CY E. HYMAN

SRI INTERNATIONAL
333 RAVENSWOOD AVENUE
MENLO PARK, CA 94025
01CY ATTN J. CASPER
01CY ATTN DONALD NEILSON
01CY ATTN ALAN BURNS
01CY ATTN G. SMITH
01CY ATTN R. TSUNODA
01CY ATTN DAVID A. JOHNSON
01CY ATTN WALTER G. CHESNUT
01CY ATTN CHARLES L. RINO
01CY ATTN WALTER JAYE
01CY ATTN J. VICKREY
01CY ATTN RAY L. LEADABRAND
01CY ATTN G. CARPENTER
01CY ATTN G. PRICE
01CY ATTN R. LIVINGSTON
01CY ATTN V. GONZALES
01CY ATTN D. MCDANIEL

TECHNOLOGY INTERNATIONAL CORP
75 WIGGINS AVENUE
BEDFORD, MA 01730
01CY ATTN W.P. BOQUIST

TRW DEFENSE & SPACE SYS GROUP
ONE SPACE PARK
REDONDO BEACH, CA 90278
01CY ATTN R. K. PLEBUCH
01CY ATTN S. ALTSCHULER
01CY ATTN D. DEE
01CY ATTN D/ STOCKWELL
SNTF/1575

VISIDYNE
SOUTH BEDFORD STREET
BURLINGTON, MA 01803
01CY ATTN W. REIDY
01CY ATTN J. CARPENTER
01CY ATTN C. HUMPHREY

UNIVERSITY OF PITTSBURGH
PITTSBURGH, PA 15213
01CY ATTN: N. ZABUSKY

END

1-87

DTIC